European Commission

Retaining structures II – design of embedded walls

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Outline of talk

Scope and contents

Design situations and limit states

Basis of design for embedded walls

Verification of strength

- Limiting equilibrium
- Soil-structure interaction analysis
- Numerical methods

Verification of serviceability

Supervision, monitoring, and maintenance

Summary of key points

Retaining structures II – design of embedded walls

SCOPE AND CONTENTS

Scope of EN 1997-1 Section 9 Retaining structures

- Gravity walls – covered in separate lecture
- Embedded walls
  - Relatively thin walls of steel, reinforced concrete, or timber
    - Supported by anchorages, struts, and/or passive earth pressure
  - The bending capacity of such walls plays a significant role in the support of the retained material
  - e.g. cantilever steel sheet pile walls; anchored or strutted steel or concrete sheet pile walls; diaphragm walls
- Composite retaining structures
  - Walls composed of elements of the above two types
  - e.g. double sheet pile wall cofferdams; earth structures reinforced by tendons, geotextiles, or grouting; structures with multiple rows of ground anchorages or soil nails
- Silos are covered by EN 1991-4

Contents of EN 1997-1 Section 9 Retaining structures

Section 9 applies to retaining structures supporting ground (i.e. soil, rock, or backfill) and/or water

§9.1 General (6 paragraphs)
§9.2 Limit states (4)
§9.3 Actions, geometrical data and design situations (26)
§9.4 Design and construction considerations (10)
§9.5 Determination of earth pressures (23)
§9.6 Water pressures (5)
§9.7 Ultimate limit state design (26)
§9.8 Serviceability limit state design (14)

Scope of EN 1997-1 Section 8 Anchors

Anchorage transmits a tensile force to a load bearing formation of soil or rock

Pre-stressed anchorage

- Anchor head + tendon free length + tendon bond length (grouted in ground)

Non pre-stressed anchorage

- Anchor head + tendon free length + restraint (e.g. Fixed length grouted in ground, deadman anchor, screw anchor, rock bolt)

Anchorages comprising tension piles shall be designed according to Section 7

Section 8 applies to design of temporary and permanent anchorages to:

- Support retaining structures
- Stabilize slopes, cuts, or tunnels
- Resist uplift forces on structures

Soil nails are NOT covered (see BS 8006 and EN 14490 instead)

Contents of EN 1997-1 Section 8 Anchorages

Section 8 of Eurocode 7 Part 1 applies to pre-stressed and non pre-stressed anchorages

§8.1 General (12/6 paragraphs)
§8.2 Limit states (1/4)
§8.3 Design situations and actions (2)
§8.4 Design and construction considerations (15)
§8.5 Ultimate limit state design (10)
§8.6 Serviceability limit state design (6)
§8.7 Suitability tests (4)
§8.8 Acceptance tests (3)
§8.9 Supervision and monitoring (1)

Contents of EN 1997-1's Annexes for retaining structures

Annex C of Eurocode 7 Part 1 provides informative text relevant to retaining structures

Annex C Sample procedures to determine earth pressures (21 paragraphs)

- §C.1 Limit values of earth pressure (3 paragraphs)
- §C.2 Analytical procedure for obtaining limiting active and passive earth pressures (14)
- §C.3 Movements to mobilise earth pressures (4)

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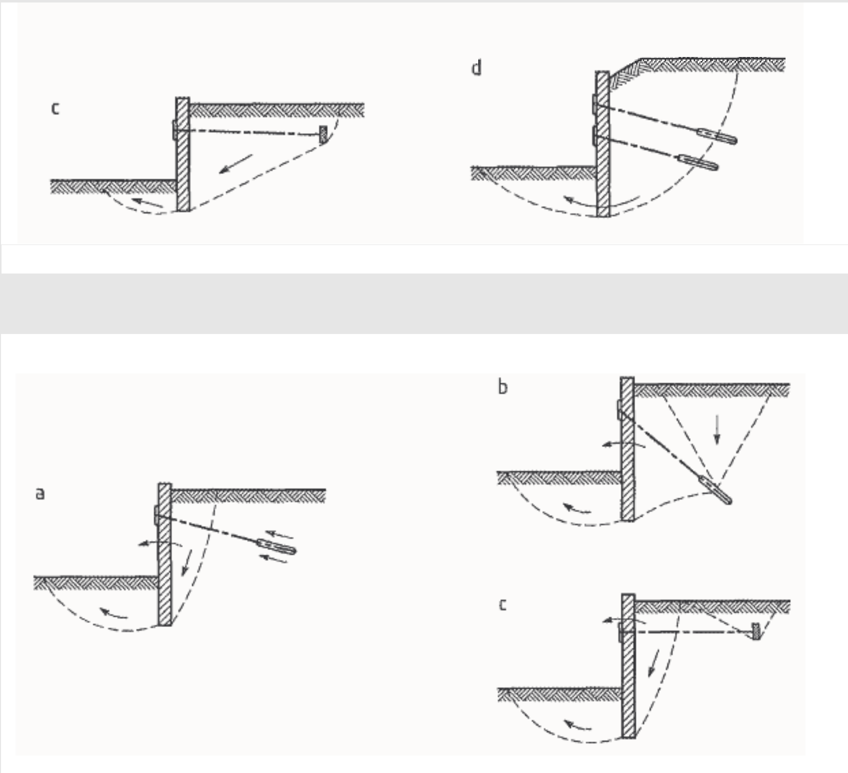
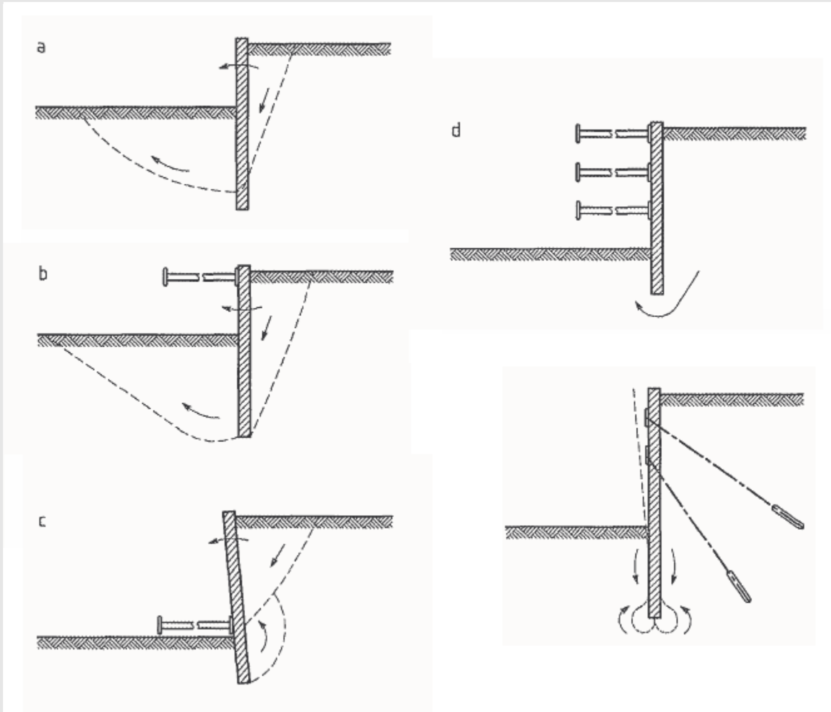
DESIGN SITUATIONS AND LIMIT STATES

Limit modes for overall stability and foundation failures (Figs 9.1, 9.3-4, & 9.6)





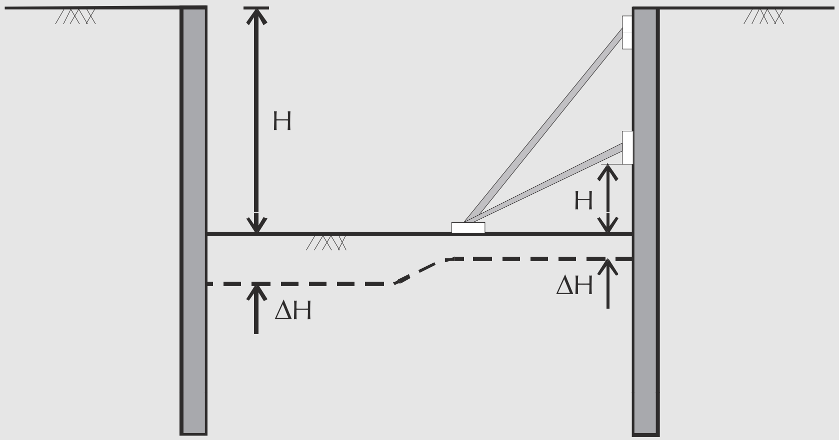
Anticipated and unplanned excavations §9.3.2.2.(2)

Design geometry shall account for anticipated excavation or possible scour in front of the retaining structure

For ULS verifications:

$$H_d = H_{nom} + \Delta H$$

Wall type	For normal site control ΔH
Cantilever	10% H
Supported	10% height below lowest prop
Maximum	0.5 m



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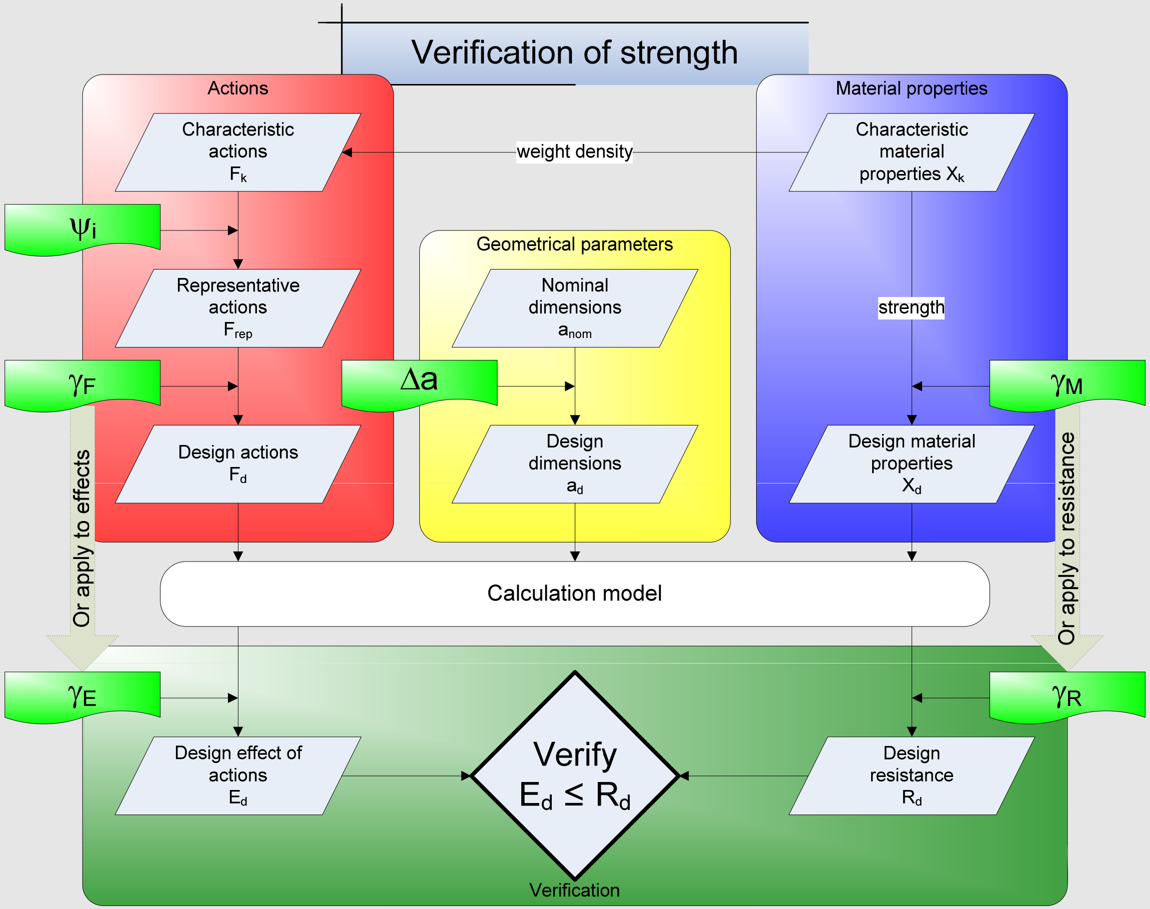
BASIS OF DESIGN FOR EMBEDDED WALLS

Verification of strength for GEO/STR (Bond & Harris, 2008)



Design Approaches explained

Design Approach			
1		2	3
Combination 1	Combination 2		
Actions	Material properties	Actions/effects & resistances	Structural actions/effects & material properties
A1 + M1 + R1	A2 + M2 + R1	A1 + M1 + R2	A1/A2 + M2 + R3

(Major) factors >> 1.0; (minor) factors > 1.0
A1-A2 = factors on actions/effects
M1-M2 = factors on material properties
R1-R3 = factors on resistances

Partial factors for GEO/STR (DA1): footings, walls, and slopes

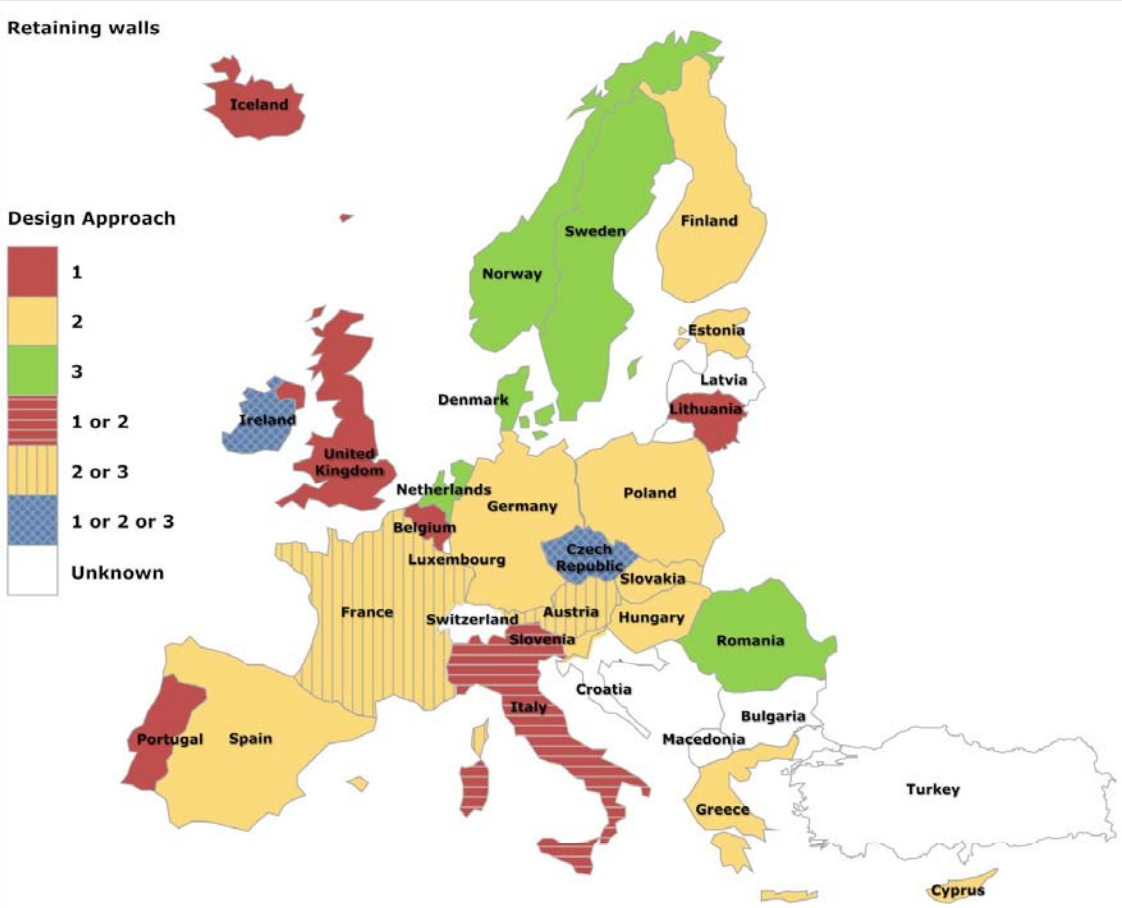
<table>
<tr><th colspan="2" rowspan="2">Parameter</th><th rowspan="2">Symbol</th><th colspan="3">Combination 1</th><th colspan="3">Combination 2</th></tr>
<tr><th>A1</th><th>M1</th><th>R1</th><th>A2</th><th>M2</th><th>R1</th></tr>
<tr><td rowspan="2">Permanent action (G)</td><td>Unfavourable</td><td>γ_G</td><td>1.35</td><td></td><td></td><td rowspan="2">1.0</td><td></td><td></td></tr>
<tr><td>Favourable</td><td>$(\gamma_{G,fav})$</td><td>1.0</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Variable action (Q)</td><td>Unfavourable</td><td>γ_Q</td><td>1.5</td><td></td><td></td><td>1.3</td><td></td><td></td></tr>
<tr><td>Favourable</td><td>-</td><td>(0)</td><td></td><td></td><td>(0)</td><td></td><td></td></tr>
<tr><td colspan="2">Shearing resistance (tan φ)</td><td>γ_φ</td><td></td><td rowspan="5">1.0</td><td></td><td></td><td rowspan="2">1.25</td><td></td></tr>
<tr><td colspan="2">Effective cohesion (c′)</td><td>γ_c</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Undrained shear strength (c_u)</td><td>γ_{cu}</td><td></td><td></td><td></td><td rowspan="2">1.4</td><td></td></tr>
<tr><td colspan="2">Unconfined compressive strength (q_u)</td><td>γ_{qu}</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Weight density (γ)</td><td>γ_γ</td><td></td><td></td><td></td><td>1.0</td><td></td></tr>
<tr><td colspan="2">Bearing resistance (R_v)</td><td>γ_{Rv}</td><td></td><td></td><td rowspan="3">1.0</td><td></td><td></td><td rowspan="3">1.0</td></tr>
<tr><td colspan="2">Sliding resistance (R_h)</td><td>γ_{Rh}</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Earth resistance (R_e)</td><td>γ_{Re}</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="9">Factors given for persistent and transient design situations</td></tr>
</table>

Partial factors for GEO / STR (DAs 2 / 3): footings, walls, slopes

Parameter		Symbol	Design Approach 2			Design Approach 3			
			A1	M1	R2	A1[#]	A2*	M2	R3
Permanent action (G)	Unfavourable	γ_G	1.35			1.35	1.0		
	Favourable	($\gamma_{G,fav}$)	1.0						
Variable action (Q)	Unfavourable	γ_Q	1.5			1.5	1.3		
	Favourable	-	(0)			(0)			
Shearing resistance (tan φ)		γ_φ						1.25	
Effective cohesion (c′)		γ_c							
Undrained shear strength (c_u)		γ_{cu}		1.0				1.4	
Unconfined comp. str. (q_u)		γ_{qu}							
Weight density (γ)		γ_γ						1.0	
Bearing resistance (R_v)		γ_{Rv}			1.4				
Sliding resistance (R_h)		γ_{Rh}			1.1				1.0
Earth resistance (R_e) walls		γ_{Re}			1.4				
Earth resistance (R_e) slopes					1.1				

Factors given for persistent and transient design situations
[#]Applied to structural actions; *applied to geotechnical actions

National choice of Design Approach for retaining walls



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VERIFICATION OF STRENGTH: LIMITING EQUILIBRIUM

Active and passive limit states (Annex C)

Eurocode 7 Part 1 (+Corrigendum 1) gives expressions for active/passive earth pressures:

$$\sigma_a = K_a \left(\int_0^z \gamma dz + q - u \right) - 2c\sqrt{K_a(1 + a/c)} + u$$

$$\sigma_p = K_p \left(\int_0^z \gamma dz + q - u \right) + 2c\sqrt{K_p(1 + a/c)} + u$$

$\sigma_a(z)$, $\sigma_p(z)$ = active/passive stress normal to wall at depth z

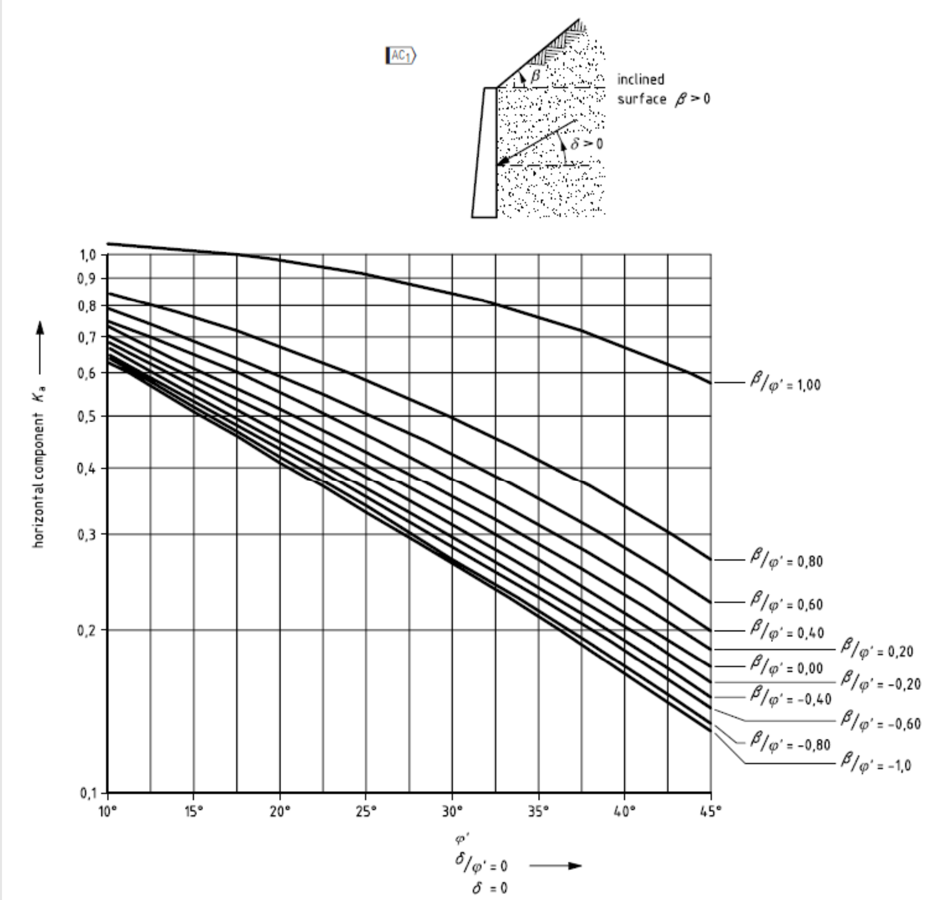
K_a, K_p = horizontal active/passive earth pressure coefficient

γ = weight density of retained ground; c = ground cohesion

q = vertical surface load; z = distance down face of wall

a = wall adhesion

Charts of earth pressure coefficients (based on Kerisel & Absi) from EN 1997-1



‘New’ formulation for active and passive earth coefficients (Annex C)

$$\sigma'_a = K_{a\gamma}\left(\int_0^z \gamma dz - u\right) + K_{aq} q - K_{ac} c$$

$$\sigma'_p = K_{p\gamma}\left(\int_0^z \gamma dz - u\right) + K_{pq} q + K_{pc} c$$

$$\left.\begin{matrix} K_{a\gamma} \\ K_{p\gamma} \end{matrix}\right\} = K_n \times \cos\beta \times \cos(\beta - \theta)$$

$$\left.\begin{matrix} K_{aq} \\ K_{pq} \end{matrix}\right\} = K_n \times \cos^2\beta$$

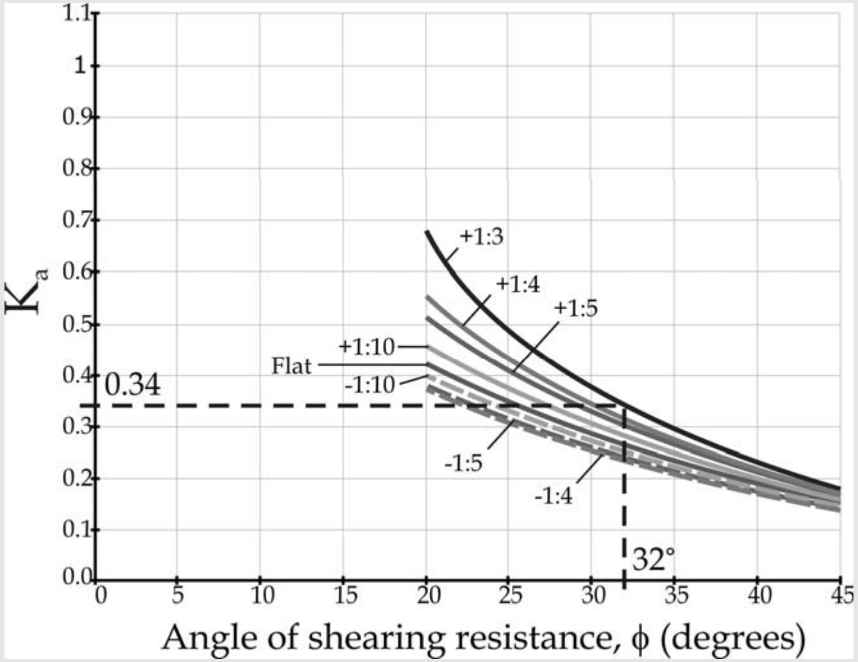
$$\left.\begin{matrix} K_{ac} \\ K_{pc} \end{matrix}\right\} = (K_n - 1) \times \cot\varphi$$

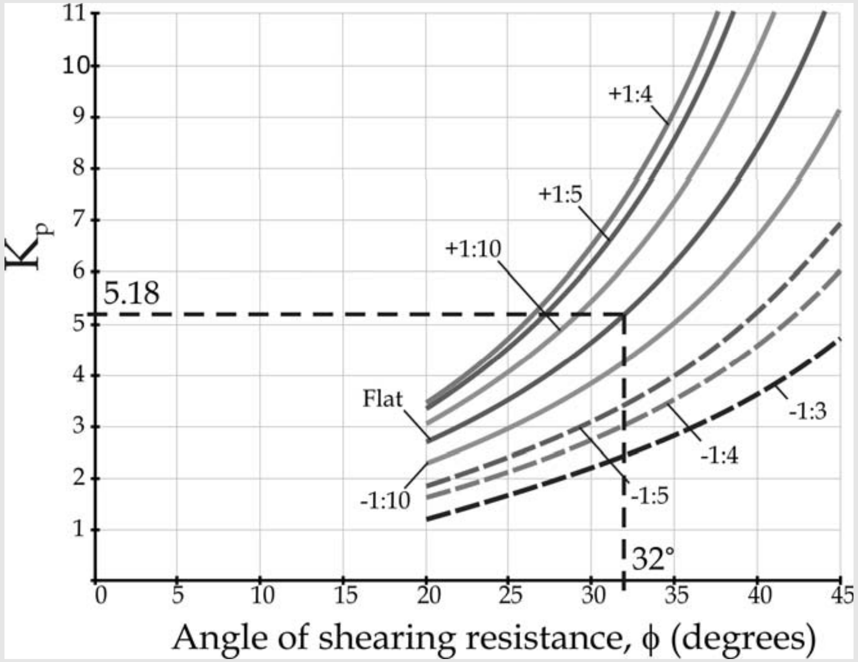
$$2m_t = \cos^{-1}\left(\frac{-\sin\beta}{\pm\sin\varphi}\right) \mp \varphi - \beta$$

$$2m_w = \cos^{-1}\left(\frac{\sin\delta}{\sin\varphi}\right) \mp \varphi \mp \delta$$

$$K_n = \frac{1 \pm \sin\varphi \times \sin(2m_w \pm \varphi)}{1 \mp \sin\varphi \times \sin(2m_t \pm \varphi)} e^{\pm 2(m_t + \beta - m_w - \theta)\tan\varphi}$$

Charts of earth pressure coefficients based on Brinch Hansen (Bond & Harris, 2008)





Angle of interface friction §9.5.1(6)

Eurocode 7 suggests δ_d is determined from soil's design *constant-volume* angle of shearing resistance $\varphi_{cv,d}$

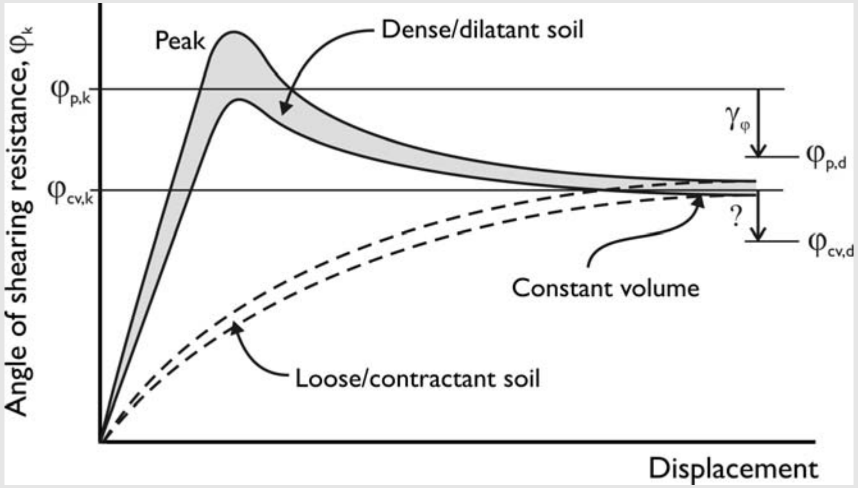
Values of k are:

- 1 for soil against cast in-situ concrete
- ⅔ for soil against precast concrete

UK National Annex states:

- *It might be more appropriate to select the design value of φ_{cv} directly*

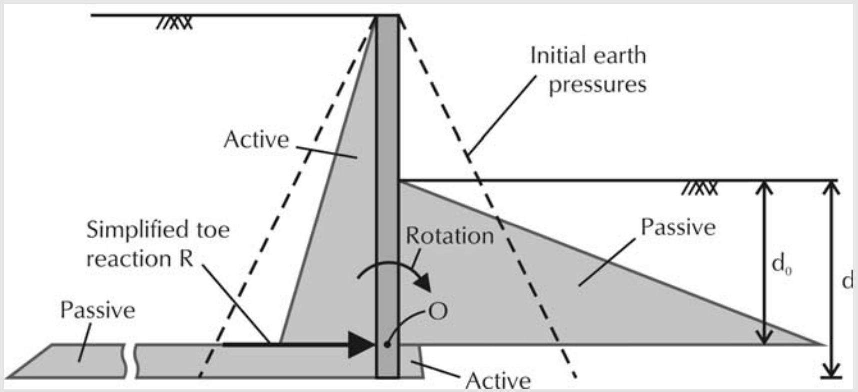
Perhaps it is better to use $\gamma_{\varphi,cv} < \gamma_\varphi$ to determine $\varphi_{cv,d}$?

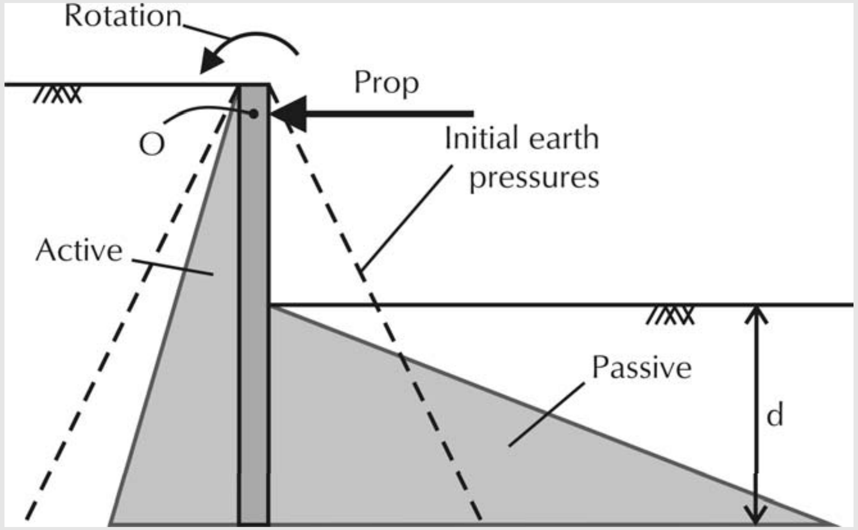


$$\delta_d = k\varphi_{cv,d} = k\tan^{-1}\left(\frac{\tan\varphi_{cv,k}}{\gamma_\varphi}\right)$$

$$\delta_d = k\varphi_{cv,d} = k\tan^{-1}\left(\frac{\tan\varphi_{cv,k}}{\gamma_{\varphi,cv}}\right)?$$

Fixed vs free earth conditions (Bond & Harris, 2008)





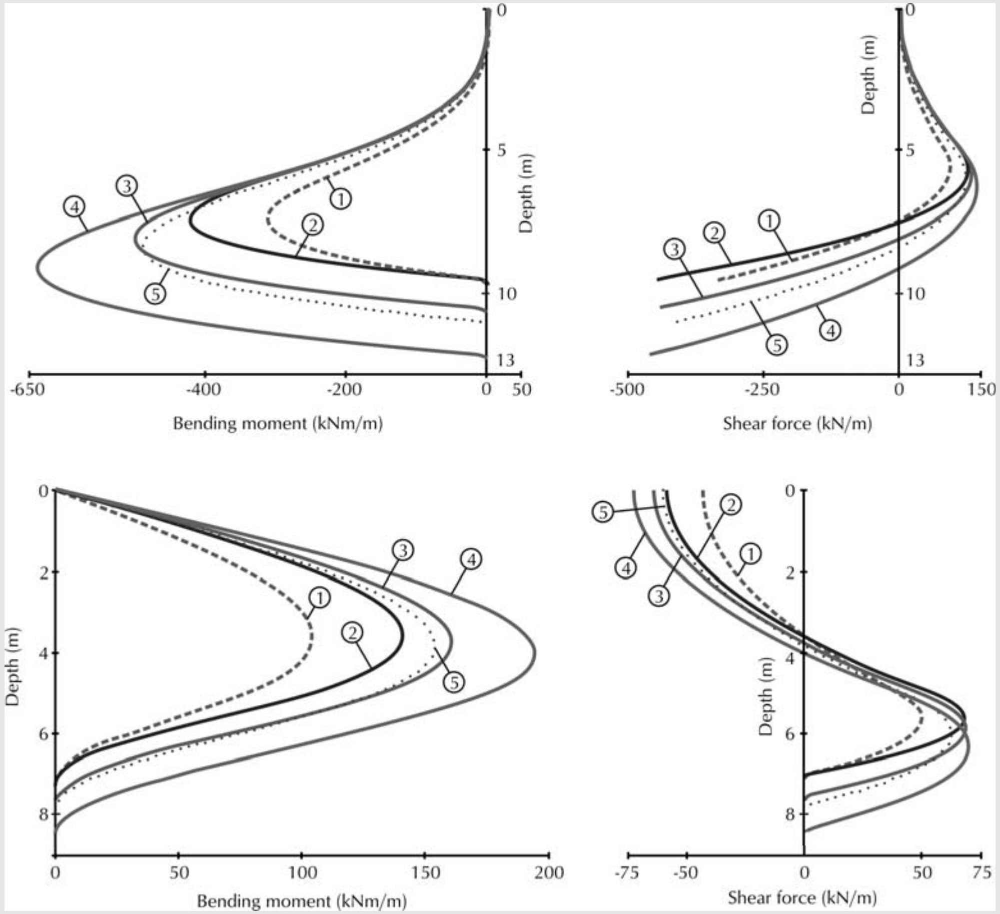
Are passive earth pressures an action or resistance?

Assumption made about passive earth pressure		Partial factors applied to...		
		Shearing resistance ($\tan \varphi_k$)	Earth pressure: Active (σ_{ak})	Earth pressure: Passive (σ_{pk})
1	SLS	÷ 1.0	× 1.0	× 1.0
2	Unfavourable action	÷ γ_φ = 1.0	× γ_G = 1.35	× γ_G = 1.35
3	Favourable action	÷ γ_φ = 1.0	× γ_G = 1.35	× $\gamma_{G,fav}$ = 1.0
4	Resistance	÷ γ_φ = 1.0	× γ_G = 1.35	÷ γ_{Re} = 1.4
5	(Doesn't matter)	÷ γ_φ = 1.25	× 1.0	× 1.0

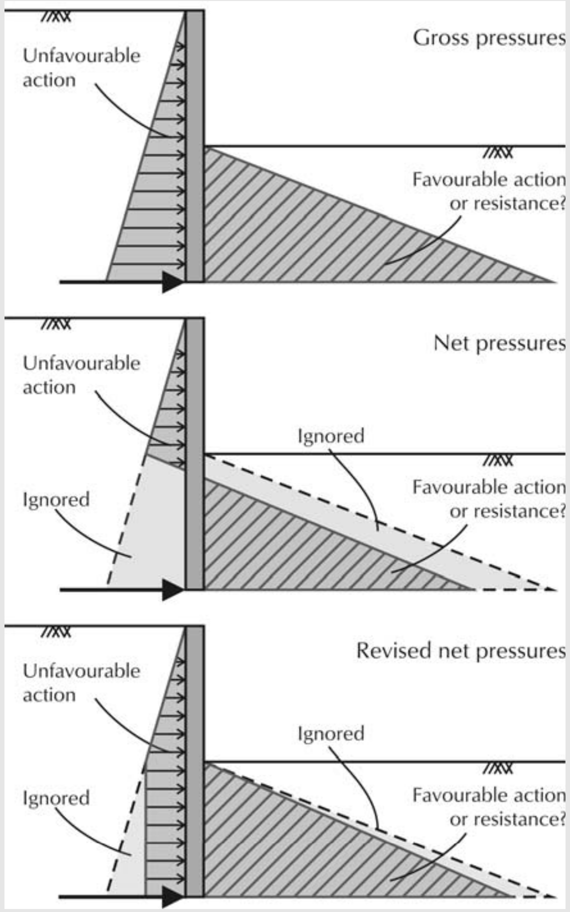
"Unfavourable (or destabilising) and favourable (stabilising) permanent actions may in some situations be considered as coming from a single source. If … so, a single partial factor may be applied to the sum of these actions or to the sum of their effects"

EN 1997-1 §2.4.2(9) NOTE

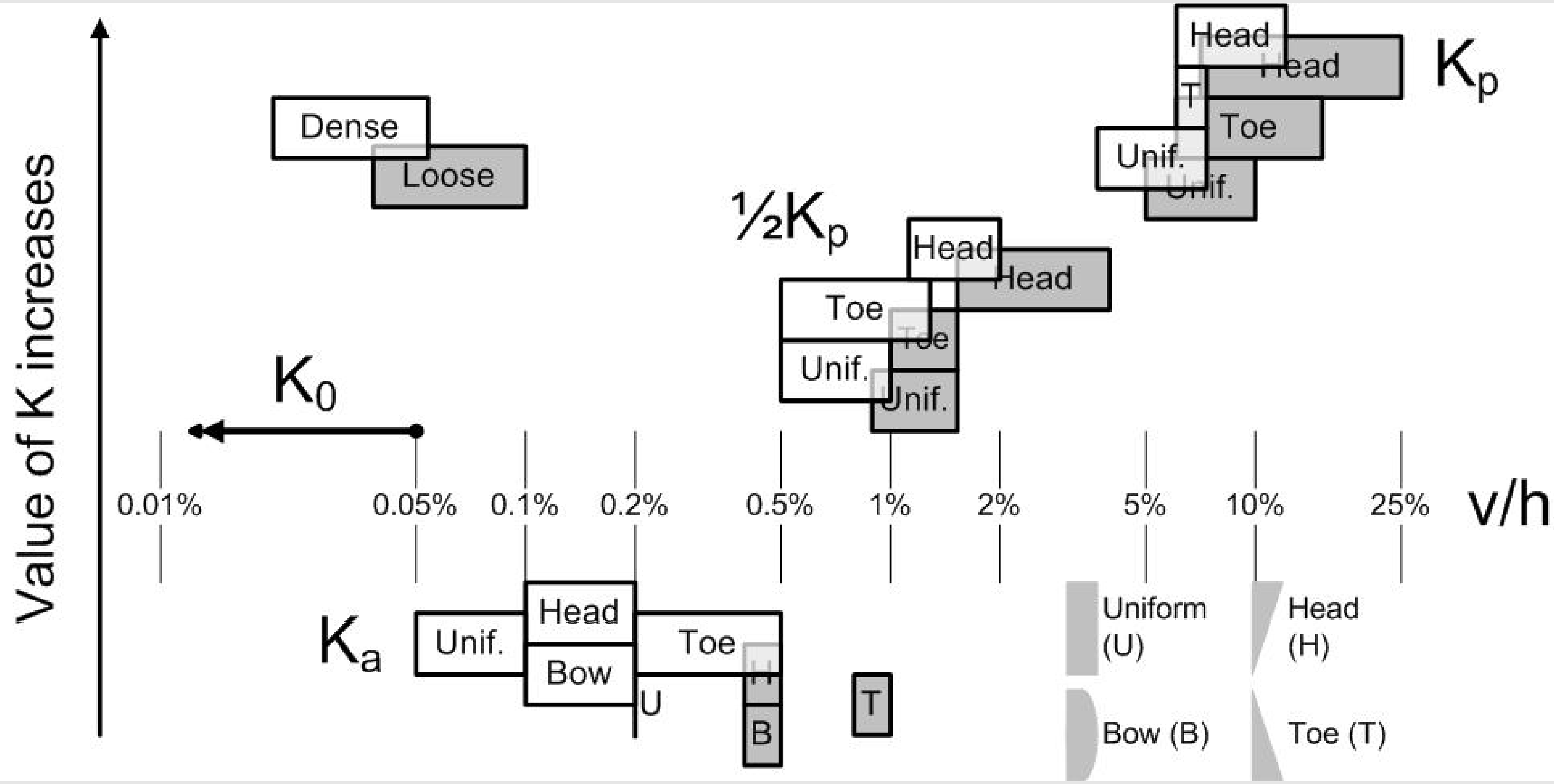
Possible outcomes vary greatly! (Bond and Harris, 2008)



Should the outcome depend on details of the calculation? (Bond & Harris, 2008)



Movement needed to trigger limiting states (Bond & Harris, 2008)



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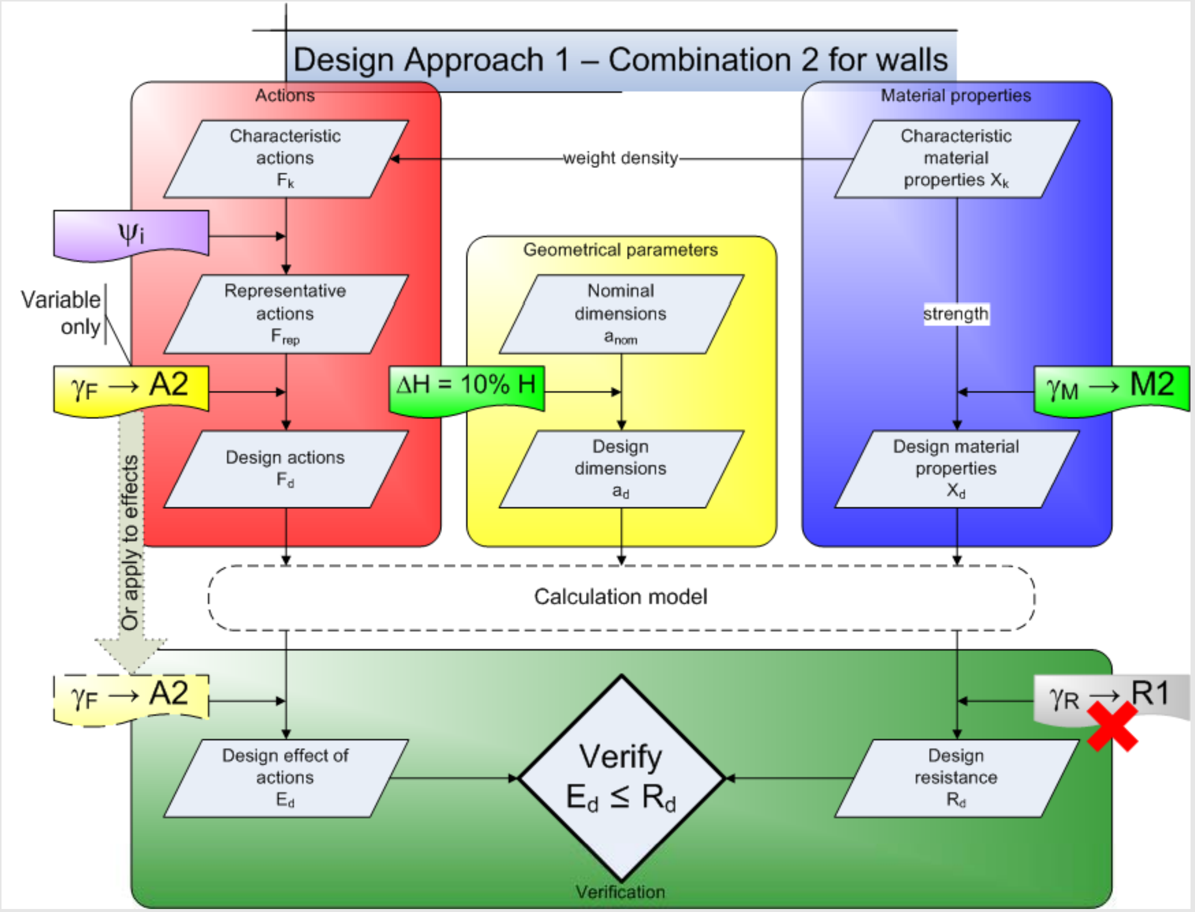
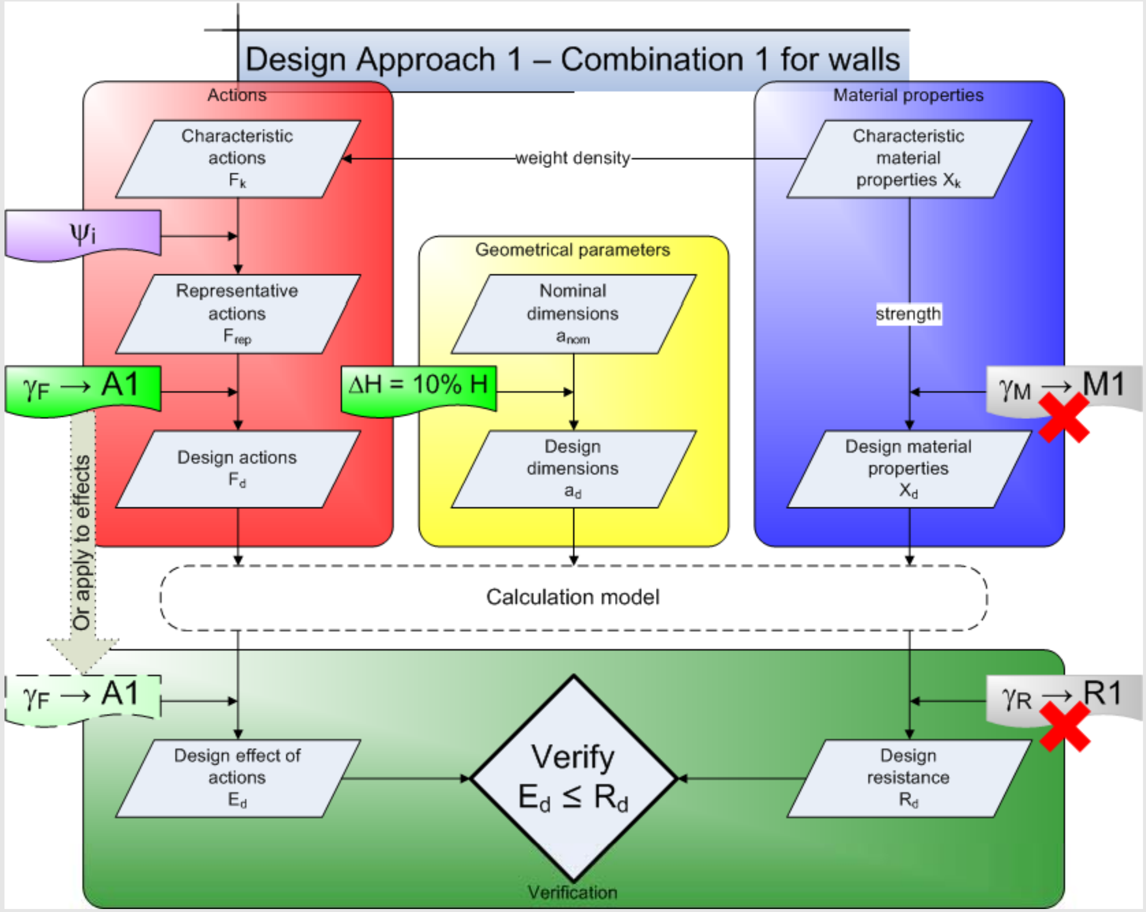
VERIFICATION OF STRENGTH: THE 'STAR' APPROACH TO DA1-1

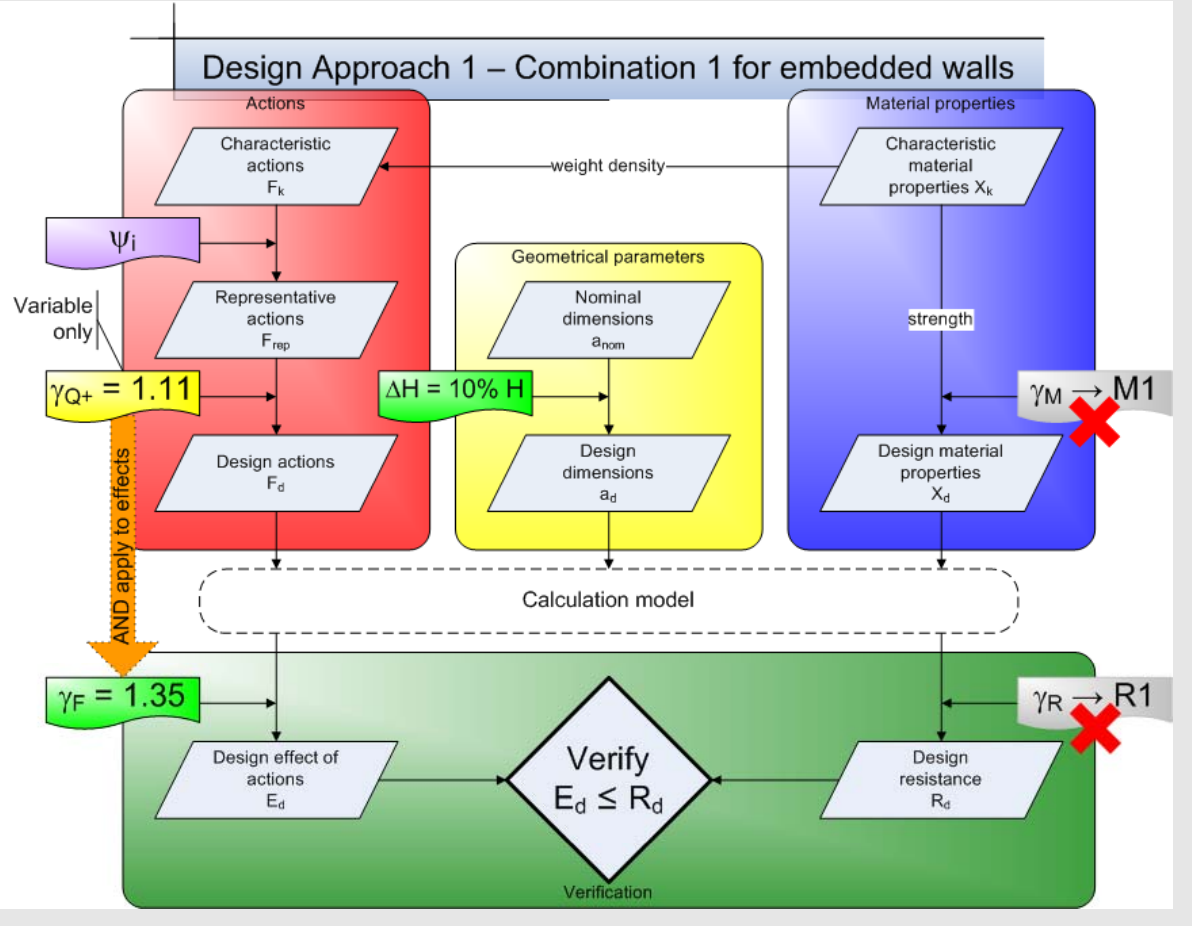
Verification of strength DA1-2 for embedded walls (Bond & Harris, 2008)



Verification of strength using DA1-1 for embedded walls (Bond & Harris, 2008)



Verification of strength using DA1-1* for embedded walls (Bond & Harris, 2008)



Using DA1-1* to verify ULS to Eurocode 7

Step	Factor	Design Approach			
		1		2	3
		1-1*	1-2		
1. Multiply variable actions by ratio γ_Q / γ_G	γ_Q / γ_G	1.11	1.3	1.11	1.3†
2. Apply partial factors to soil strengths	$\gamma_\varphi = \gamma_c$	1.0	1.25	1.0	1.25
	γ_{cu}	1.0	1.4	1.0	1.4
3. Perform soil structure interaction analysis					
4. Check ratio of restoring to overturning moment $M_R/M_O \geq \gamma_G \times \gamma_{Re}$	$\gamma_G \times \gamma_{Re}$	1.35	1.0	1.89	1.0
5. Apply partial factor to action effects	γ_G	1.35	1.0	1.35	1.0†
†Partial factors from Set A2 for geotechnical actions					

Retaining structures II – design of embedded walls

VERIFICATION OF SERVICEABILITY

Comparable experience is paramount

A cautious estimate of the distortion and displacement of retaining walls, and the effects on supported structures and services, shall always be made on the basis of comparable experience. This estimate shall include the effects of construction of the wall. The design may be justified by checking that the estimated displacements do not exceed the limiting values

EN 1997-1 §9.8.2(2)P

Displacement calculations shall be undertaken:

- where nearby structures and services are unusually sensitive to displacement
- where comparable experience is not well established

Displacement calculations should be considered where the wall …

- retains more than 6 m of cohesive soil of low plasticity
- retains more than 3 m of soils of high plasticity
- is supported by soft clay within its height or beneath its base

Retaining structures II –
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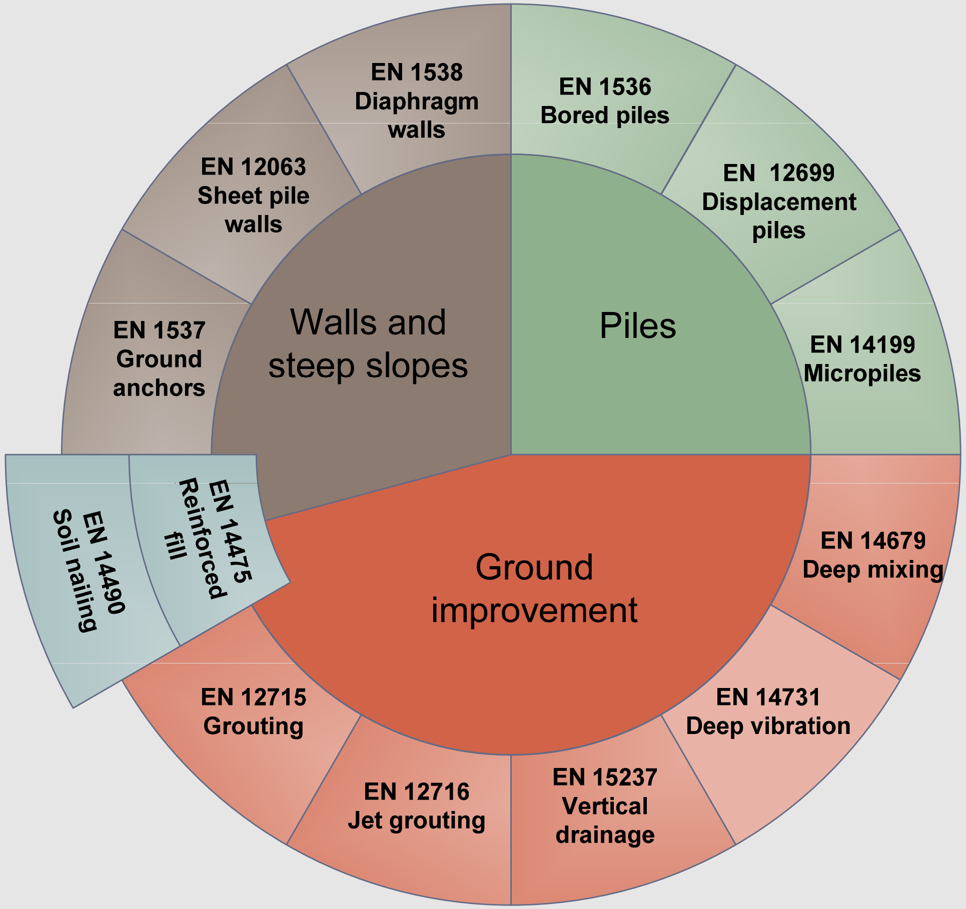
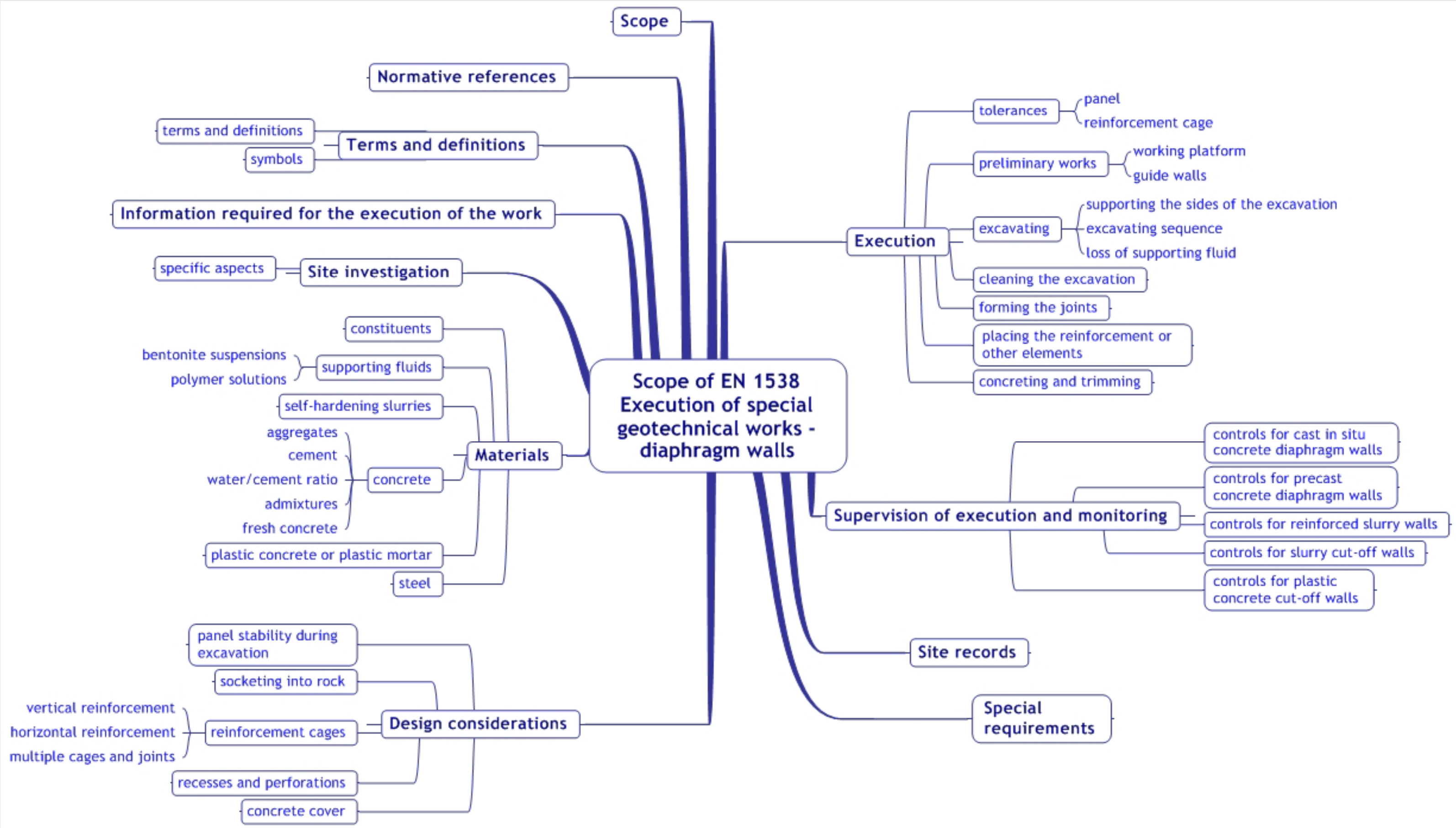
SUPERVISION, MONITORING, AND MAINTENANCE

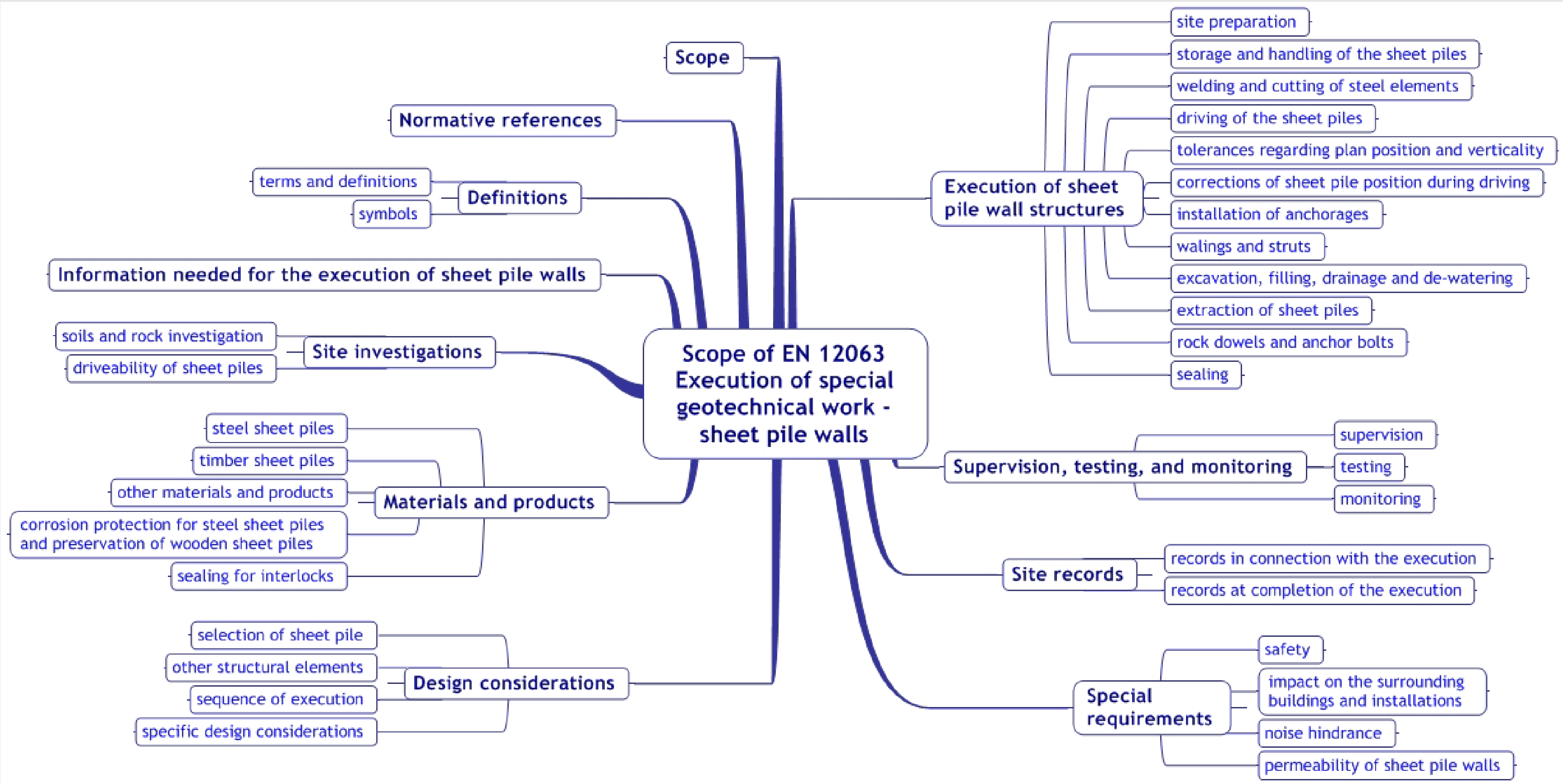
Execution of special geotechnical works (Bond and Harris, 2008)



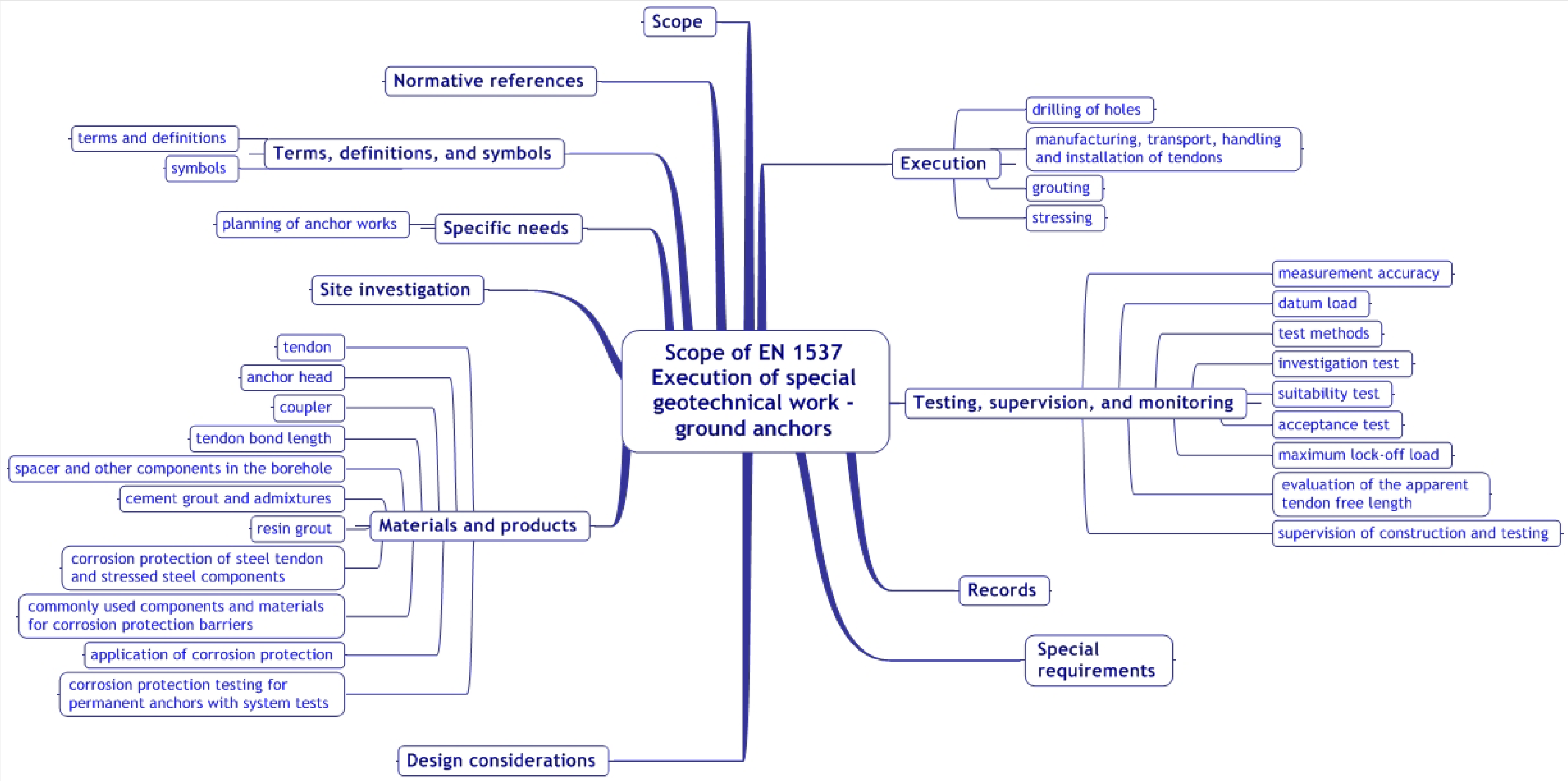
Scope of EN 1538 Execution of … diaphragm walls (Bond & Harris, 2008)



Scope of EN 12063 Execution of … sheet pile walls (Bond & Harris, 2008)



Scope of EN 1537 Execution of … ground anchors (Bond & Harris, 2008)



Retaining structures II – design of embedded walls

SUMMARY OF KEY POINTS

Summary of key points

Design of embedded walls to Eurocode 7 involves checking:

- vertical bearing capacity of the wall
- any reduction in wall friction owing to vertical loads
- stability calculations based on limiting equilibrium, soil-structure interaction, or fully numerical methods
- considerable debate about the way passive earth pressures should be handled – as a resistance, as a favourable action, or as an unfavourable action (invoking the single source principle)
- use of partial factors into sub-grade reaction and numerical models has to be done carefully

Overall impact should be:

- little change in what we build
- more thought about how we design

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